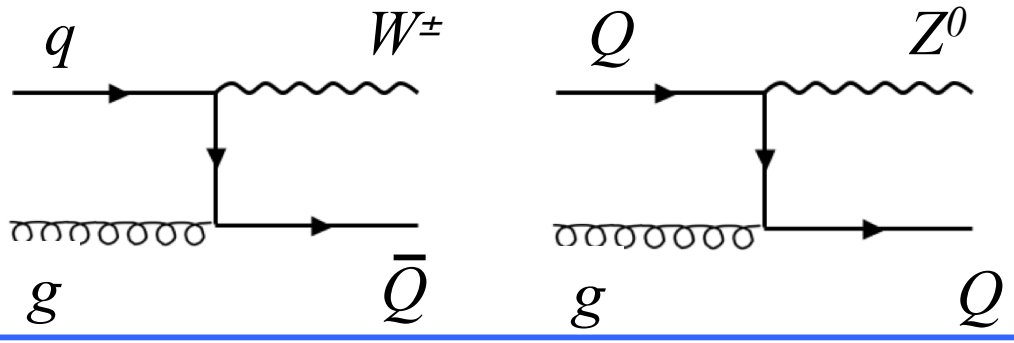
W/Z+jets and W/Z+HF Production at the Tevatron

Keith Matera
From the University of Illinois at Urbana-Champaign
on behalf of the CDF and D0 collaborations

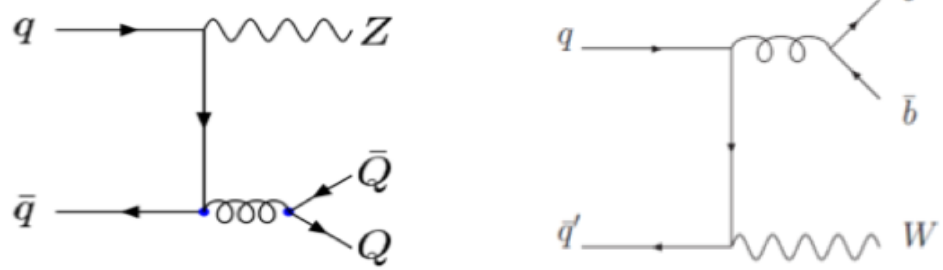
Rencontres de Moriond QCD, La Thuile (IT)
22-29 March 2014

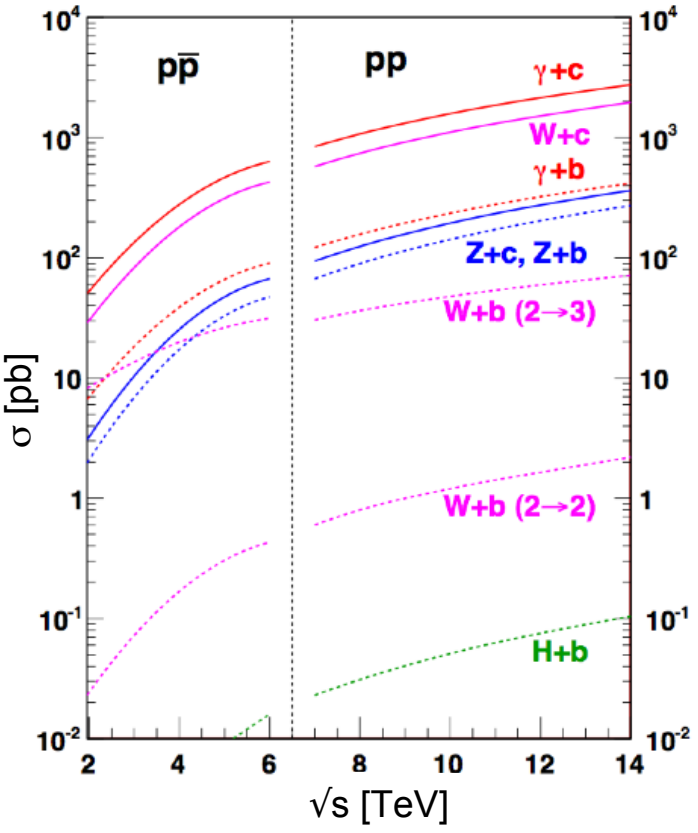
W/Z plus jets / heavy flavor production is a good probe of QCD…

- First-order production is sensitive to the proton PDF



- Provides stringent test of perturbative QCD calculations

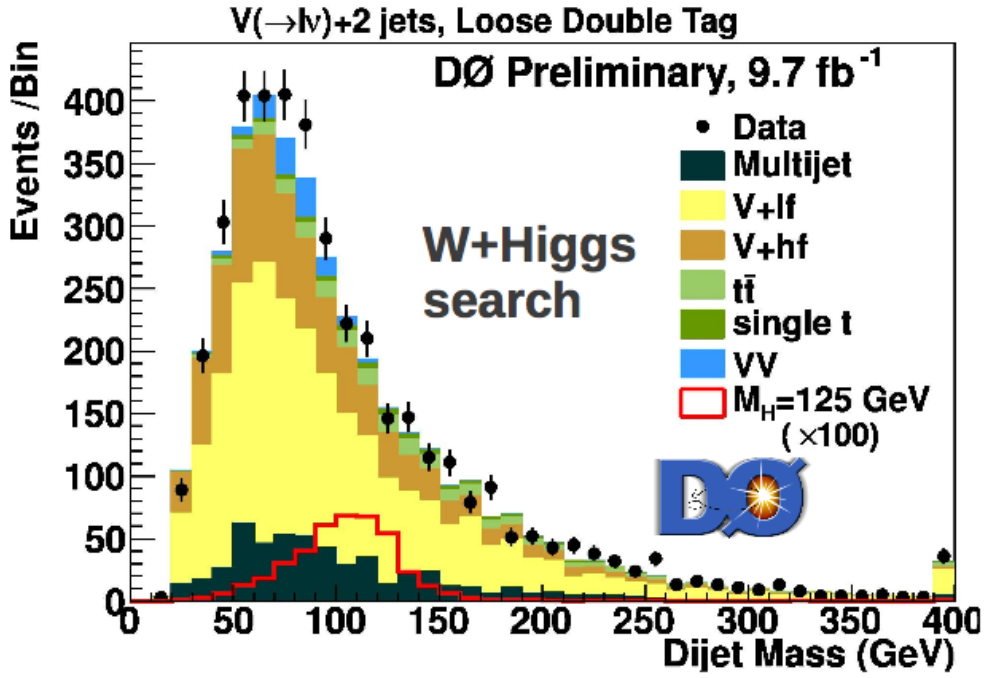




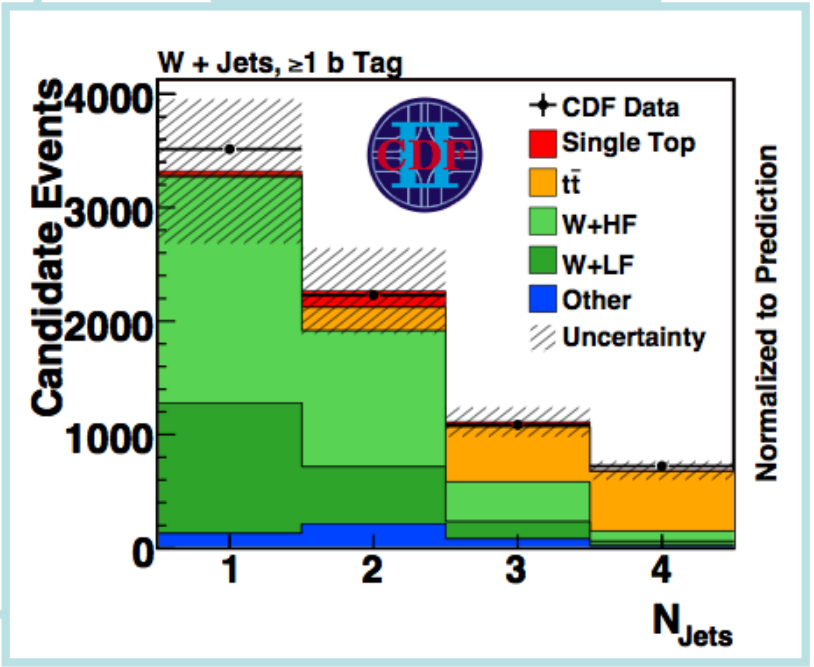
- Small h.f. σ = challenging!

…and W/Z plus jets/h.f. is an important model for background in other searches

e.g. for Higgs…



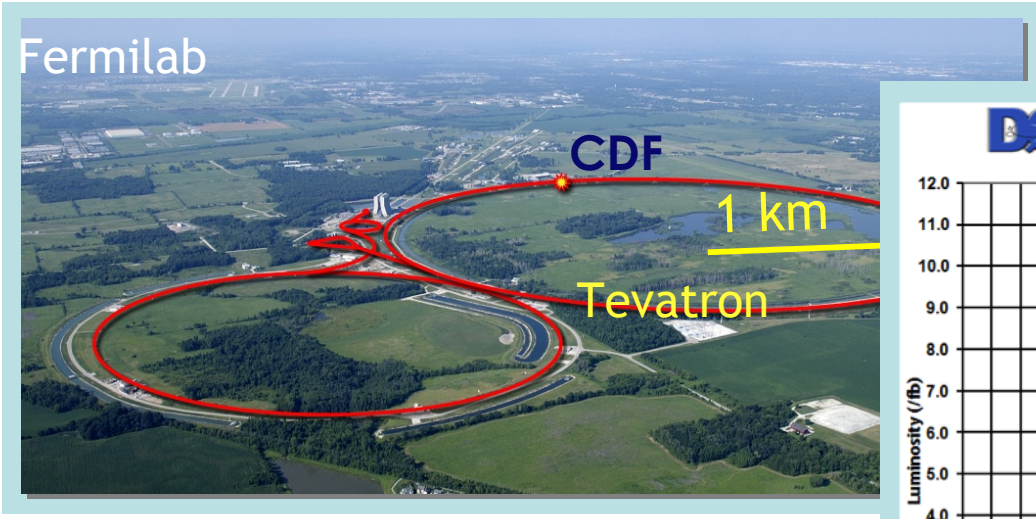
… and single top

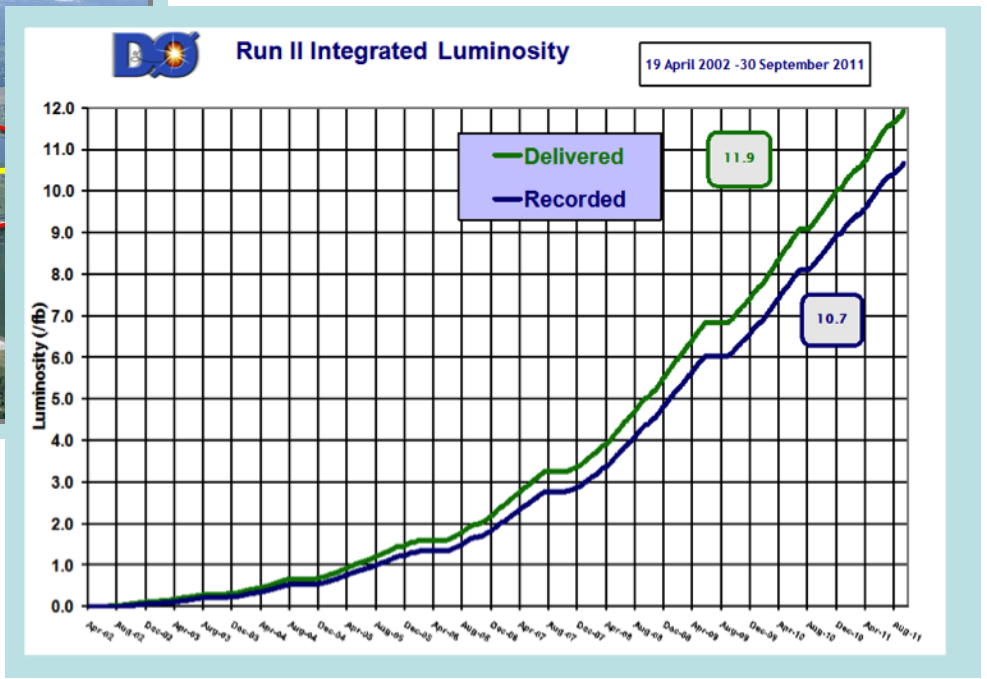


As well as new physics searches (e.g. dark matter candidates)

The Tevatron provided a decade's worth of $\sqrt{s}$ =1.96 TeV $p\bar{p}$ data

- Collided $p\bar{p}$ bunches at $\sqrt{s}$=1.96 TeV through 30/09/2011



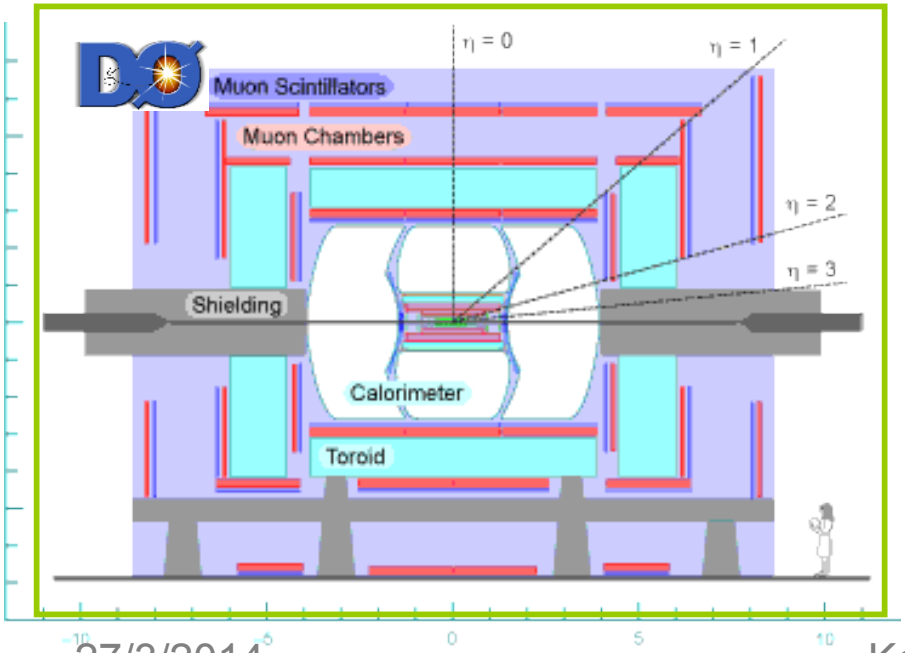


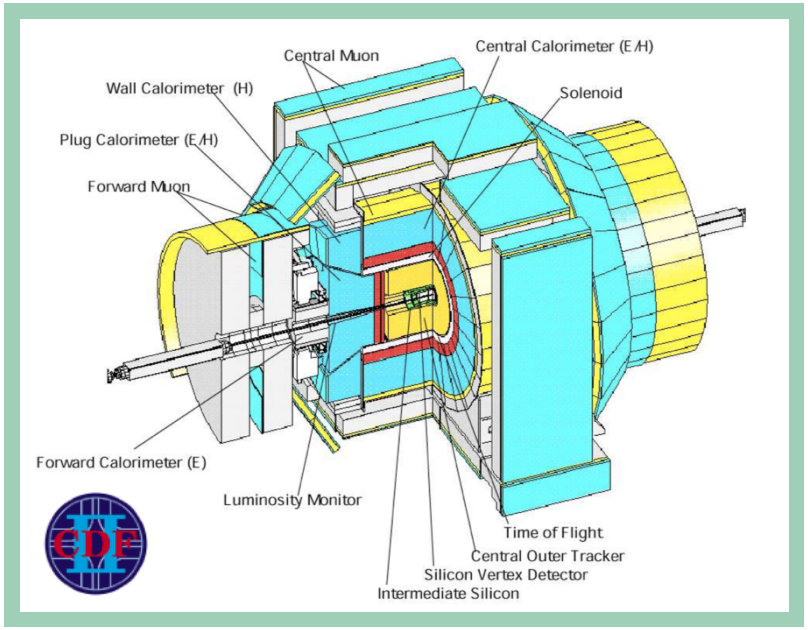
- The CDF and D0 experiments recorded up to ~10 fb^{-1} each

- Peak luminosity ~3-4 x 10^{32} cm^{-2} s^{-1}

While designed for high-p_T physics, CDF & D0 are powerful h.f. tools

- High CM energy means more species of h.f production---even compared to B factories
- Precision vertex reconstruction capabilities (CDF & D0)
- Excellent tracking for mass resolution (CDF)





- Powerful trigger on displaced vertices (CDF)
- Charge symmetric detector (D0)
- Hermitic calorimeter and excellent energy resolution (D0)

A legacy of great W/Z + jets/heavy flavor results! And now some more…

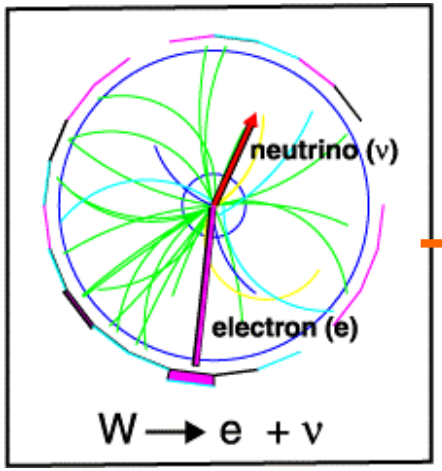
Most recently:


Final State	Luminosity	Detector	Publication
W+jets	3.7 fb^{-1}	D0	[Phys. Rev D **88**, 092001 (2013)]
Z+c	9.7 fb^{-1}	D0	[PRL **112**, 042001 (2014)]
W/Z+Y	9.1 fb^{-1}	CDF	[CDF Public Note 11007 (Preliminary)]
W/Z+D*	9.7 fb^{-1}	CDF	[CDF Public Note 11087 (Preliminary)]

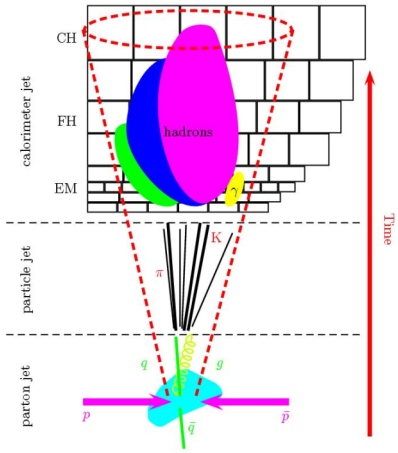
This is what we'll focus on in this talk!

A standard W/Z+jets analysis begins with a high-p_T lepton trigger

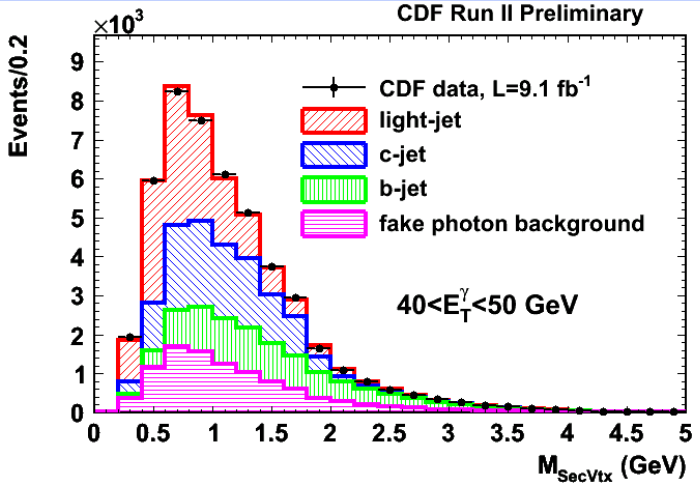
- This lepton is paired with MET (for W) or an oppositely-signed lepton (for Z)



- Midpoint jet algorithm defines jets within a cone of R=0.4-0.7

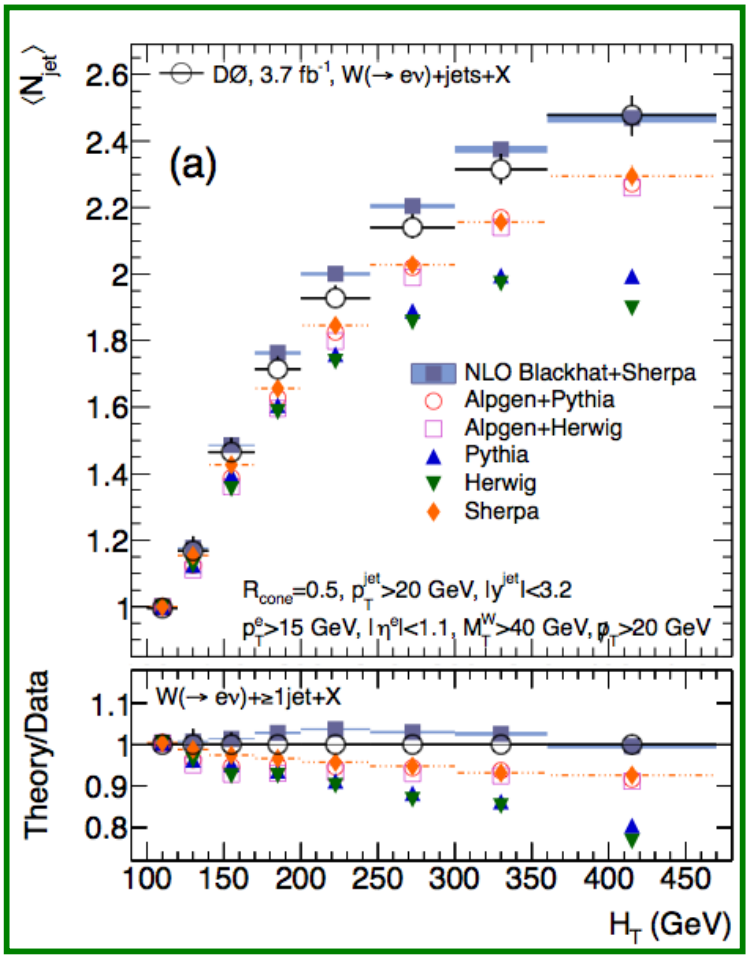


- For heavy-flavor, a secondary vertex is tagged. M_{inv} of this vertex can be fit to *bottom* / *charm* / *light flavor* profiles.
- Detector-level cross-sections are unfolded back to particle level with MC and data-driven techniques.

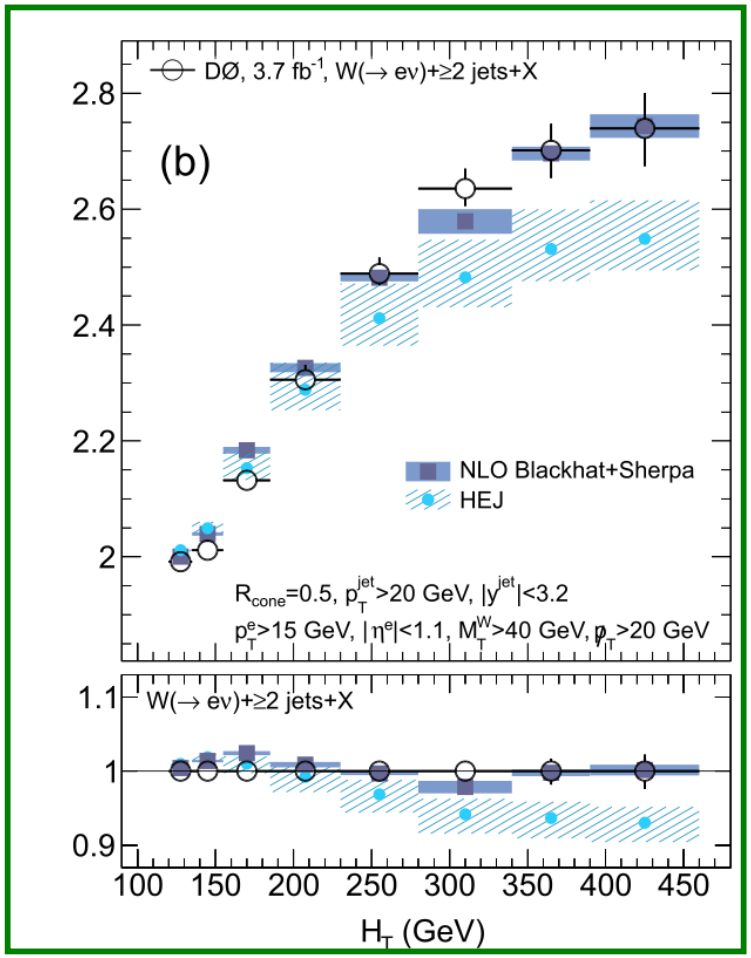


D0 expanded the set of measured observables in *W+n-jet* events at TeV.

- Comprehensive study measuring 40 differential cross-sections



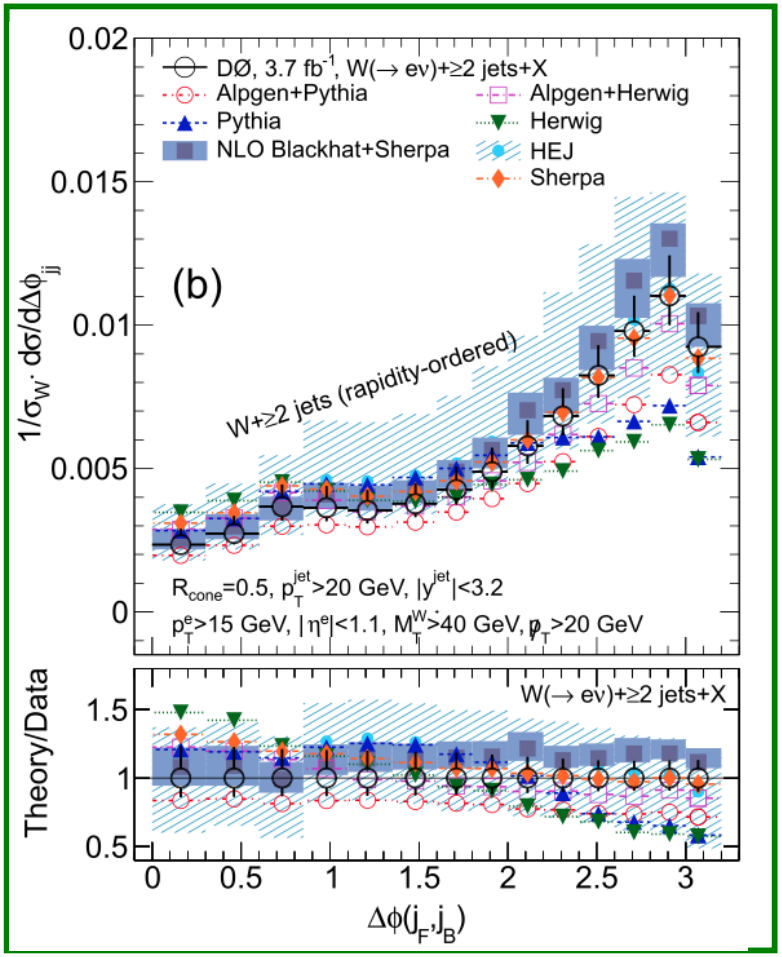
- Good agreement b/w data and NLO Blackhat
- Help in the tuning of MC
- Test of parton emission models

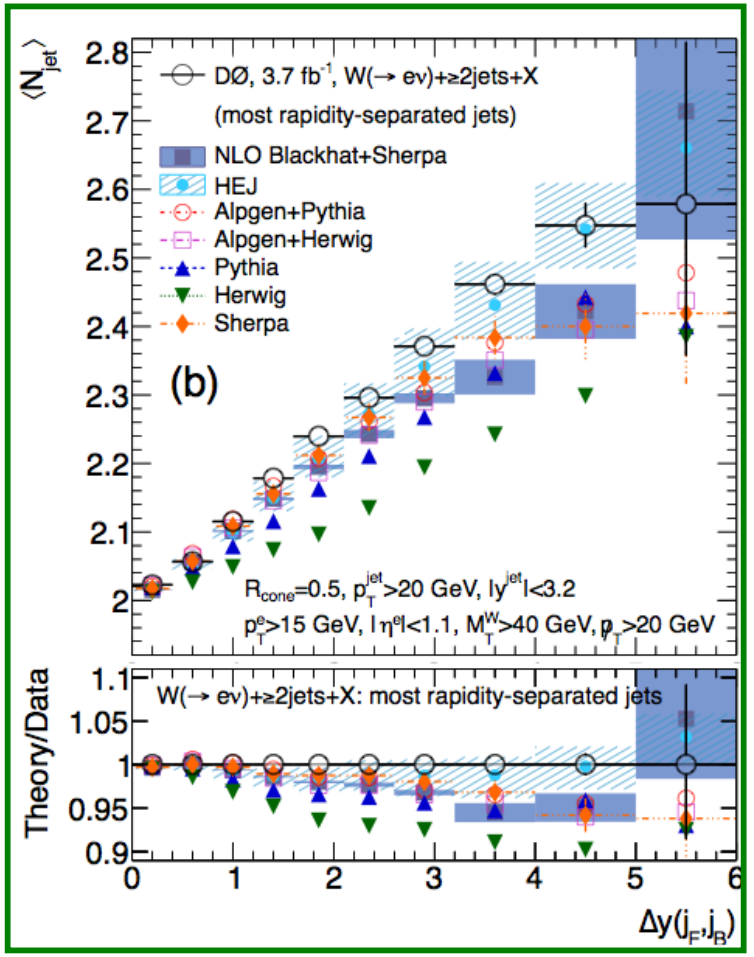


[Phys. Rev D **88**, 092001 (2013)]

D0 expanded the set of measured observables in *W+n-jet* events at TeV.

- At wide opening angle, other models provide better agreement

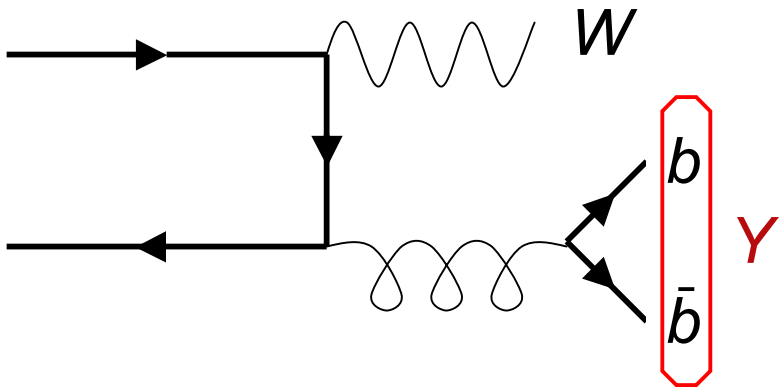




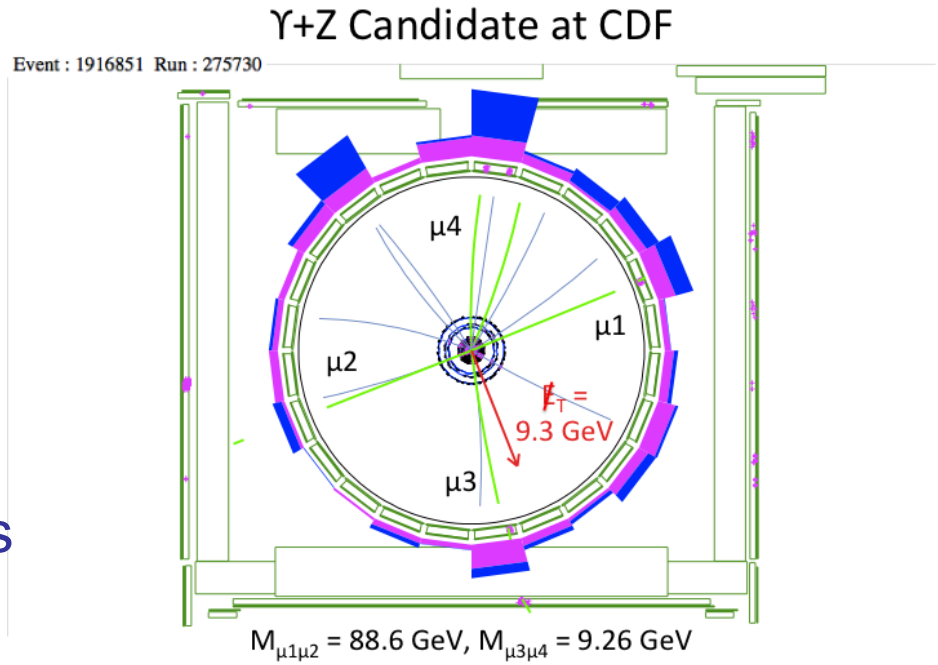
[Phys. Rev D **88**, 092001 (2013)]

New *Y+W/Z* measurements provide upper limits on SM & SUSY searches

- *Y+W/Z* is a rare process with a SM cross-section predicted to be outside the range of sensitivity of the Tevatron

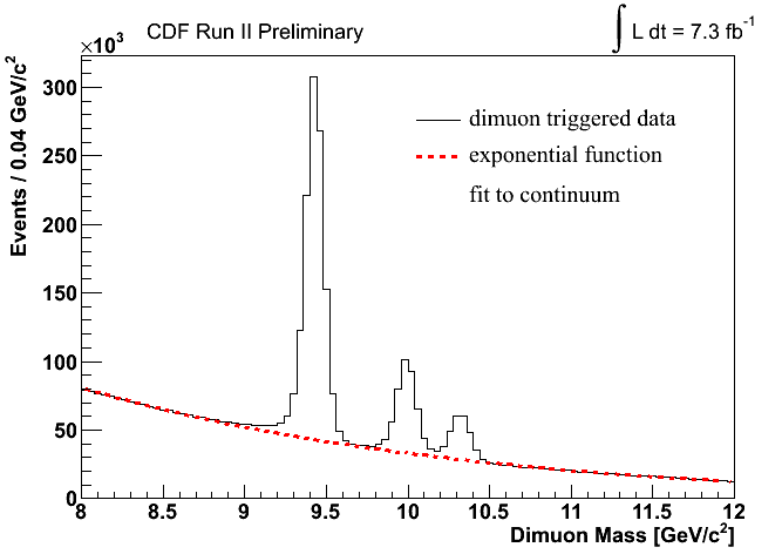


- Sensitive to non-relativistic QCD models and new physics (e.g. a SUSY *Higgs→Y+W/Z*)



[CDF Public Note 11007]

CDF has observed no *Y+W/Z* excess, setting the best σ limits on $p\bar{p} \rightarrow Y+W/Z$



- Looks for *Y(1s)*$\rightarrow\mu\mu$ and *W/Z* charged lepton decays with standard cuts
- Observes 1(1) *Y+W(Z)* candidate over an expected bkg of 1.2±0.5 (0.1±0.1) events

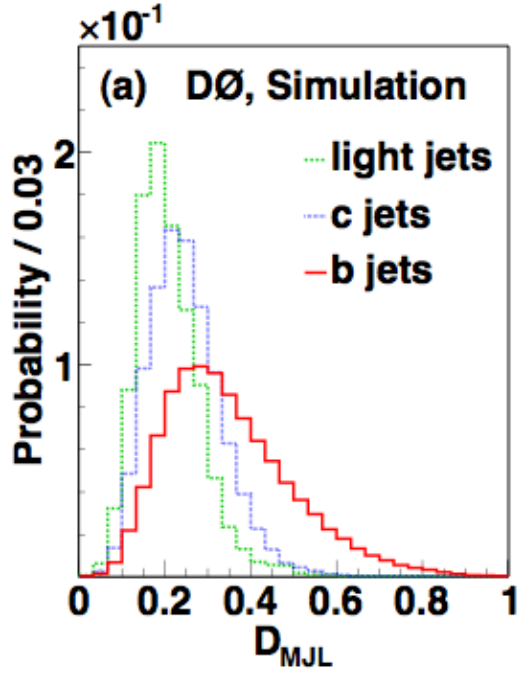
- Sets 95% C.L. cross-section limits:

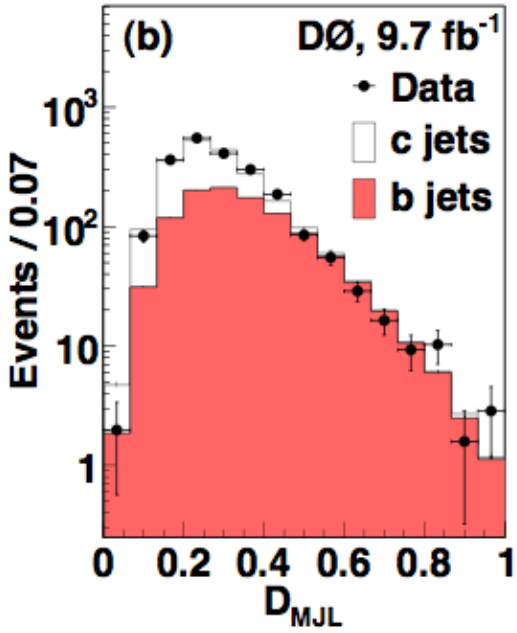
	$\Upsilon + W$	$\Upsilon + Z$
expected limit (pb)	5.4	13
observed limit (pb)	5.4	20
Run I observed limit (pb)	93	101

[CDF Public Note 11007]

Last summer, D0 announced the first observation of $Z+c_{jet}$ at the Tevatron

- Jets flavor was identified using a combination of jet properties:





Used discriminant:

D_{MJL} = 0.5 x (M_{SV}/5 GeV - ln(JLIP)/20)

M_{SV} = mass of the jet sec. vtx.
JLIP= jet lifetime impact parameter

- Jets required to have p_T >20 GeV, $|\eta|$<2.5

[PRL **112**, 042001 (2014)]

Jets in *Z* events had more charm than predicted by NLO, on average

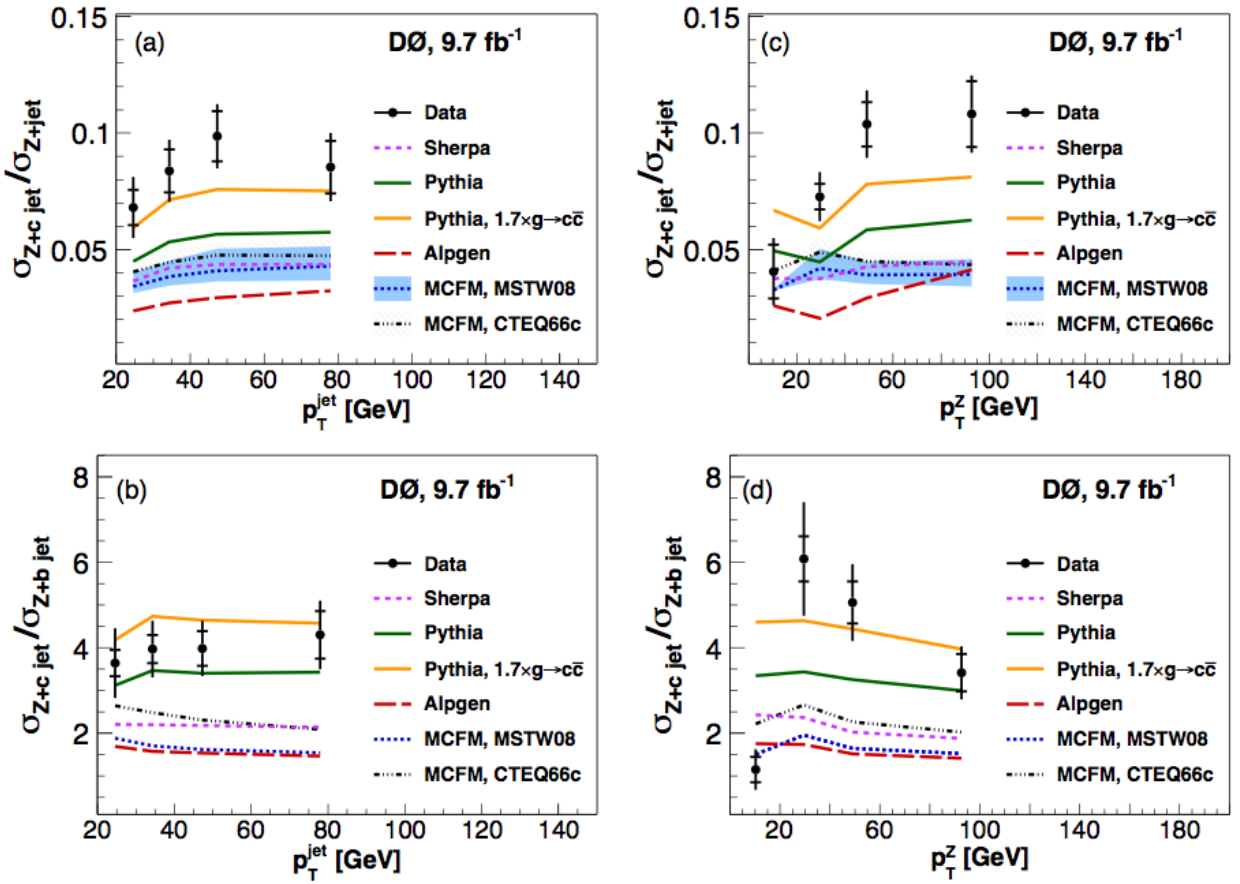
- Measures

$$\frac{\sigma(Z + c_{jet})}{\sigma(Z + \text{jet})} \text{ and } \frac{\sigma(Z + c_{jet})}{\sigma(Z + b_{jet})}$$

- Integrated *c*-jet fractions 2.5 times higher, on avg, than NLO predictions

Measured	(stat)	(syst)
$R_{c/jet}$ = 8.92	± 0.0053	± 0.0089
$R_{c/b}$ = 4.00	± 0.21	± 0.58

- Results agree best with Pythia + enhanced $g \to c\bar{c}$ splitting ratio

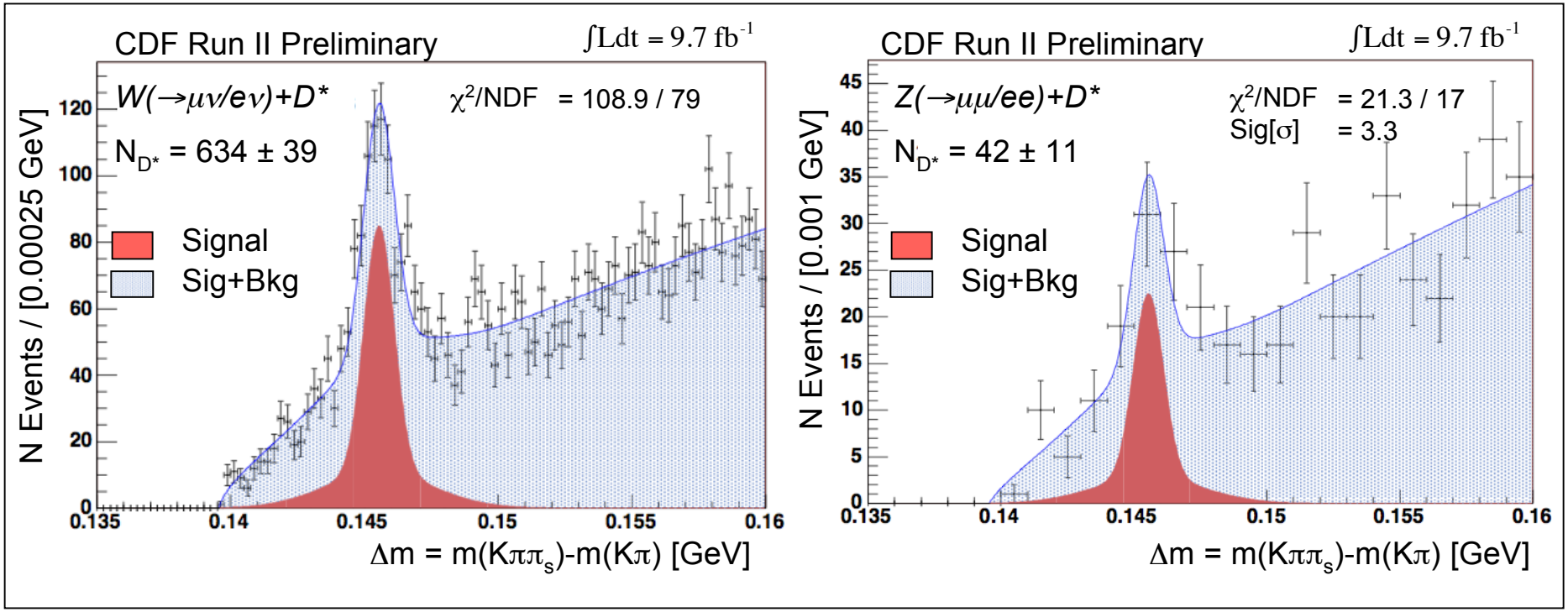


(Blue bands represent variation of scale by factors of 2, 1/2)

[PRL **112**, 042001 (2014)]

CDF has also measured $W/Z+D^*$ production for $p_T(D^*) > 3$ GeV

- Fully-reconstructs $D^{*+} \to D^0(K^-\pi^+)\pi^+$ at the track level in W/Z events



- Signal discriminant is mass difference between D^* and D^0 vertices. Background is reduced with a neural network to improve stat. unc.

[CDF Public Note 11087]

Measurements of $\sigma(W/Z+D^*)/\sigma(W/Z)$ compare favorably with simulation

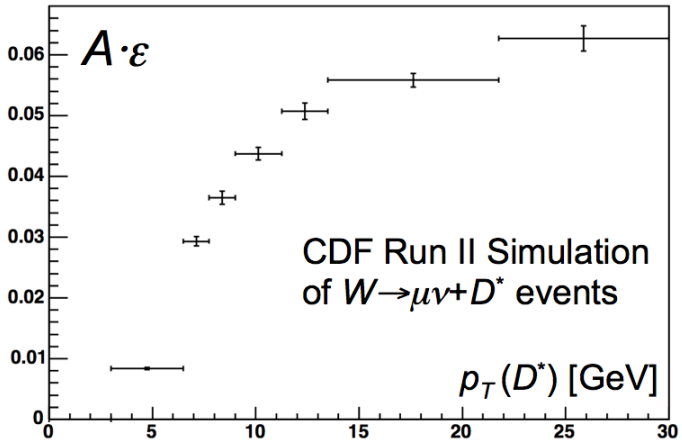
Each decay mode is considered separately:

Measured quantity for $p_T(D^*) > 3$ GeV	CDF Run II Data (%)	Pythia 6.2.16 CTEQ5L (%)
$\sigma(W_{e\nu} + D^*)/\sigma(W_{e\nu})$	$1.74 \pm 0.21 \pm 0.17$	1.77 ± 0.01
$\sigma(W_{\mu\nu} + D^*)/\sigma(W_{\mu\nu})$	$1.75 \pm 0.17 \pm 0.03$	1.77 ± 0.01
$\sigma(Z_{ee} + D^*)/\sigma(Z_{ee})$	$1.0 \pm 0.6 \pm 0.2$	1.36 ± 0.01
$\sigma(Z_{\mu\mu} + D^*)/\sigma(Z_{\mu\mu})$	$1.8 \pm 0.5 \pm 0.2$	1.36 ± 0.01

- This is the lowest-momentum measurement of charm production in vector boson events at the Tevatron (*previously > 15 GeV only*)

- Acceptance is modeled as a function of D^* p_T using Pythia MC:

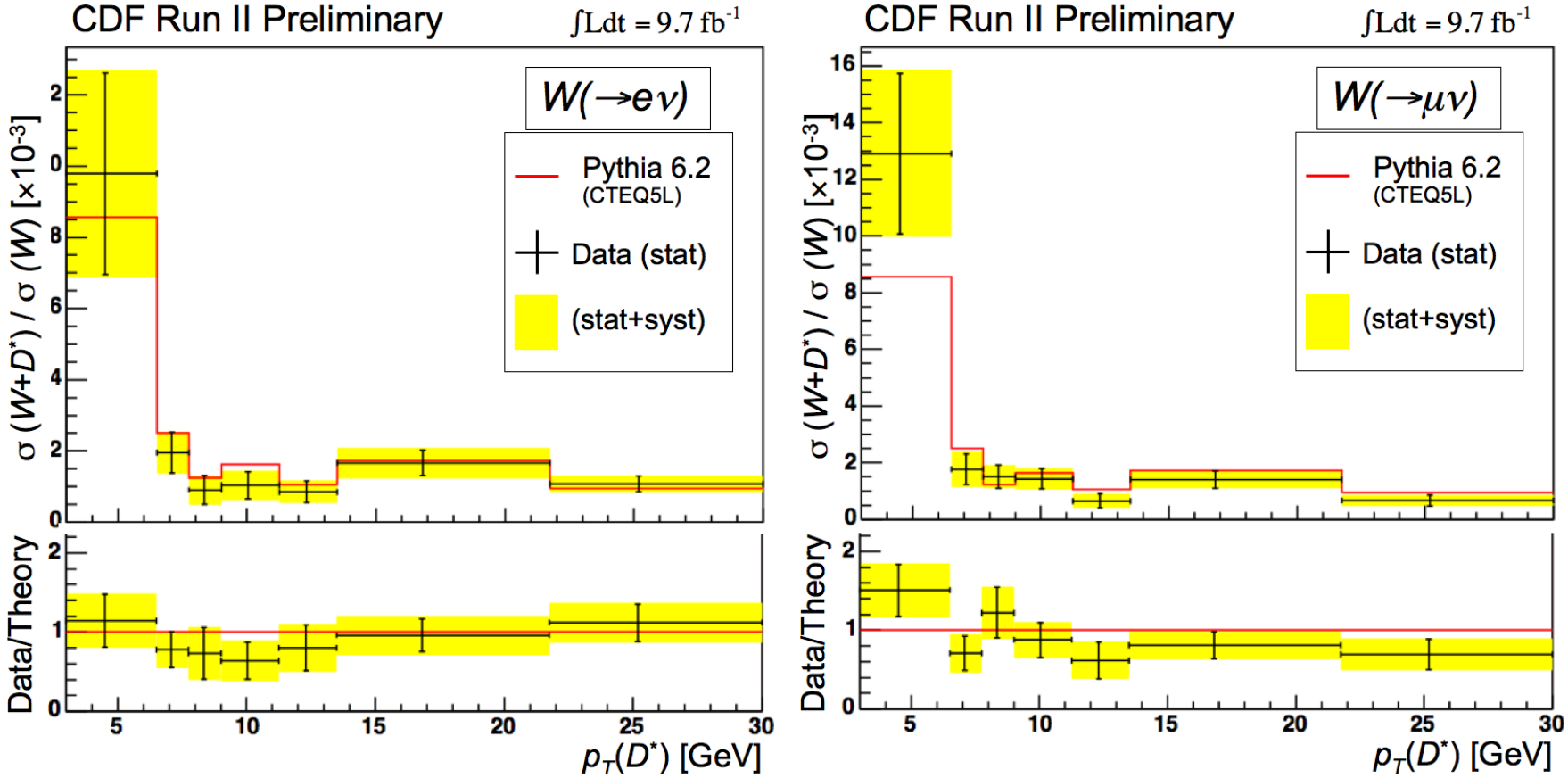
Process (with D^* understood to decay as $D^* \to D^0(\to K\pi)\pi$)	Inclusive W/Z tag rate	Inclusive $W/Z + D^*$ tag rate w/ NN ($p_T(D^*) > 3$ GeV)
$p\bar{p} \to W(\to e\nu) + D^*$	0.195	0.021341 ± 0.000002
$p\bar{p} \to W(\to \mu\nu) + D^*$	0.219	0.024171 ± 0.000002
$p\bar{p} \to Z(\to ee) + D^*$	0.482	0.009388 ± 0.000002
$p\bar{p} \to Z(\to \mu\mu) + D^*$	0.614	0.012385 ± 0.000003



[CDF Public Note 11087]

Measurements of $d\sigma(W+D^*)/\sigma(W)$ as fnct of $p_T(D^*)$ also compare favorably

- Good agreement with Pythia 6.2.16 using CTEQ5L PDF set

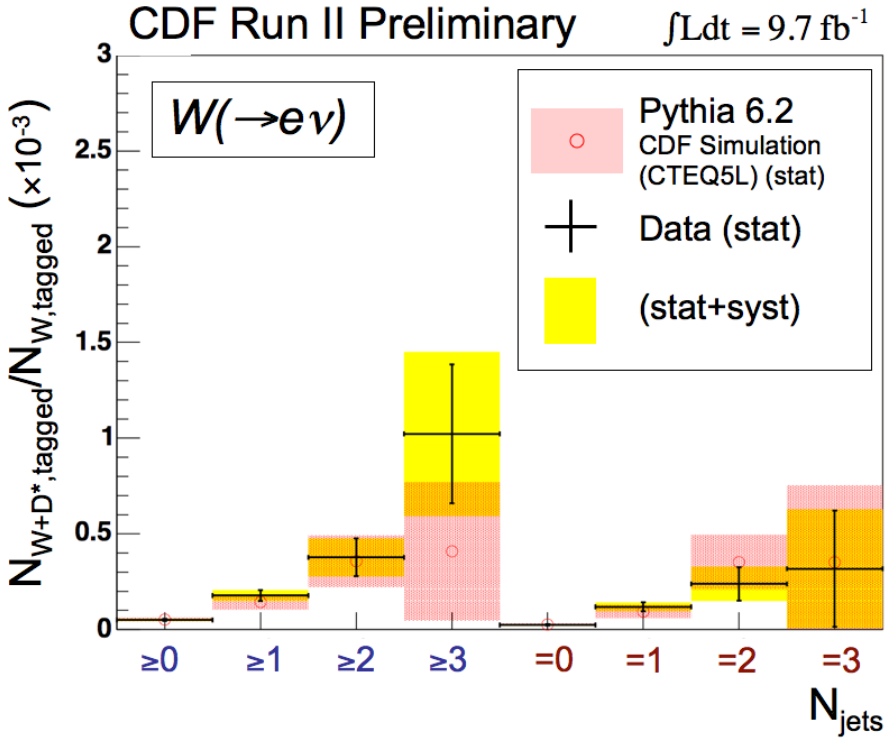


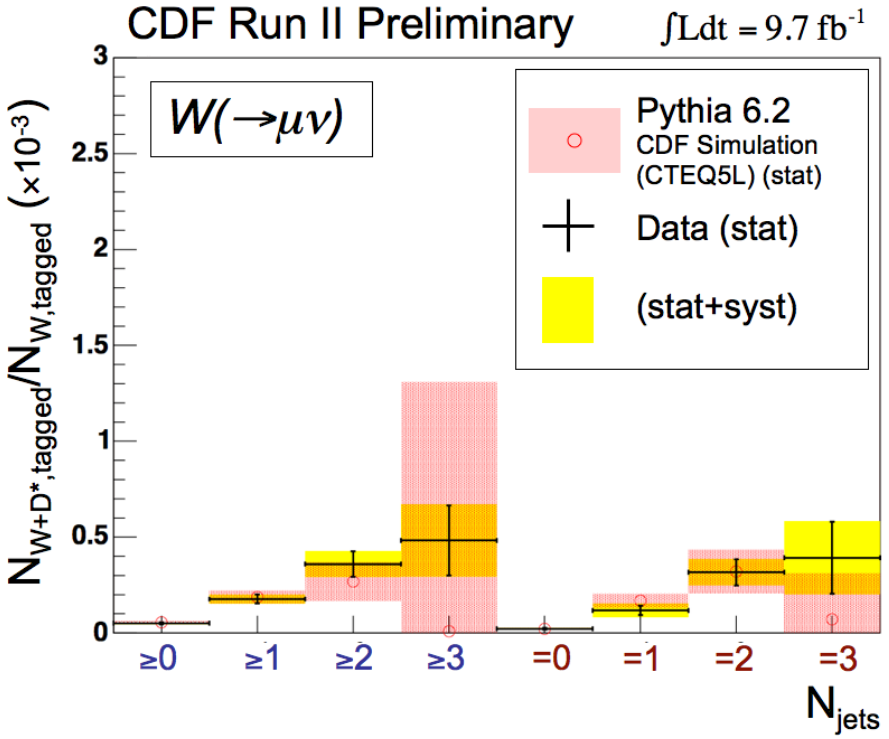
- Yellow error bands shown are at the 68% C.L.

[CDF Public Note 11087]

$\sigma(W+D^*)/\sigma(W)$ as a function of N_{jets} promises similar agreement

- Tagged event fractions are shown below (not unfolded with $A\cdot\varepsilon$)





- MC comparisons are with inclusive $W\rightarrow e\nu/\mu\nu$ production samples
- First measurement of *W+charm* in zero-jet events at the Tevatron

[CDF Public Note 11087]

Summary

- The full CDF/D0 datasets continue to provide interesting new *W+jets* and *W+h.f.* results, adding to their legacy
- In the past year, have provided two firsts in $p\bar{p}$ collisions:
  - first observation of *Z+c*
  - first observation of *W/Z+D** at low p_T ($p_T > 3$ *GeV*)
- Have also expanded the library of *W+jets* knowledge, and placed the current best limits on $p\bar{p} \rightarrow Y+W/Z$ production
- These analyses will benefit MC tunings, and many future analyses at both the Tevatron and LHC---more to come as we continue to explore the full datasets!

Further Reading

- All results discussed in this talk are available on the CDF and D0 Public Results pages:

CDF:

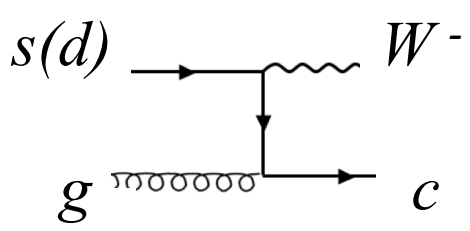
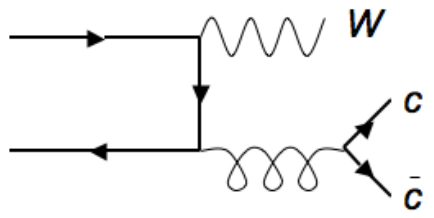
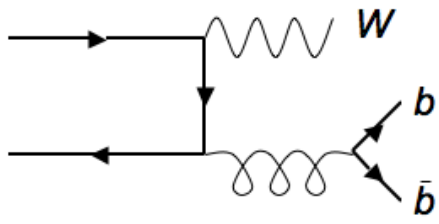
http://www-cdf.fnal.gov/physics/new/qcd/QCD.html

D0:

http://www-d0.fnal.gov/results/

CDF $W/Z+D^*$ analysis can also split the signal by production process

- There are three major contributions to our final $W+D^*$ signal:

$s(d)+g \rightarrow W+c$	$W+g(\rightarrow c\bar{c})$	$W+g(\rightarrow b\bar{b})$, $B \rightarrow D^*+X$
		
14 ± 6%	73 ± 8%	13 ± 5%

- The percentages above are derived using neural networks, and by exploiting sign correlations in the W and c of Process 1.
- Again, first measurement of these processes at low p_T (>3 GeV)!